

SENtral™ M&M

Motion & Measurement Modules

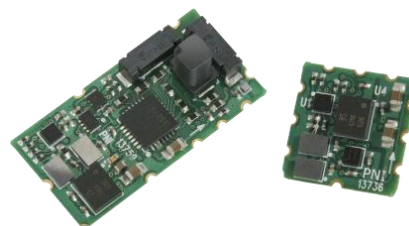
General Description

PNI's SENtral M&M motion and measurement modules provide highly accurate heading and orientation data, in a small, low-power-consumption, and easy-to-integrate package. A module incorporates the SENtral motion coprocessor, a magnetometer, an accelerometer, and a gyroscope, with different SENtral M&M versions comprising different sensor models.

Unlike other inertial measurement units (IMUs) requiring unexpected and extensive sensor fusion algorithm development and sensor calibration work, the Sentral M&M modules are pre-engineered to provide the highest accuracy motion tracking and heading measurement. And this is obtained at a fraction of the power consumption of any other solution on the market.

The SENtral M&M comes ready to integrate into a user's system. Designed with SMT bonding in mind, the pins are on an industry-standard 3 mm pitch. The on-board EEPROM contains SENtral's configuration file and this automatically uploads into SENtral RAM when powered up. Communication is via I²C protocol.

With the SENtral M&M modules you can quickly and easily incorporate industry-leading motion-tracking and orientation measurement in your mobile device. We're sure you'll be impressed.



Features

- All-in-one motion & orientation tracking module, incorporates the SENtral motion coprocessor, 3-axis gyroscope, 3-axis accelerometer, and 3-axis magnetometer.
- Low power consumption.
- 11x11 mm footprint and SMT design for ease of integration into a user's system
- Multiple test points for debugging and evaluating performance.
- Multiple versions with different sensors.

Applications

- Personal Navigation & LBS
- Gaming & Augmented Reality
- Movement Science & Fitness
- Ordering Information

Item	Sensors	Part #
White M&M	none (Sentral only)	13734
Orange M&M	BMI055+AK8963	13771
Red M&M	MPU6500+AK8963	13763
Green M&M	LSM330+AK8963	13736
Yellow M&M	LSM9SD0	13738
Blue M&M	LSM330+RM3100	13759

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1 Product Overview

The SENtral™ M&M Motion and Measurement Module is a castellated printed-circuit assembly that makes it easy to quickly integrate and evaluate a complete motion sensor fusion system into a mobile device. A module incorporates the SENtral Motion Coprocessor, a magnetometer, an accelerometer, and a gyroscope, with different SENtral M&M versions integrating different sensor models. The SENtral motion coprocessor manages and uses data from the three sensors to provide reliable motion tracking and an accurate compass heading, while consuming about 1% of the power of a comparable ARM-based sensor fusion microprocessor. SENtral outputs Euler angles (aka heading, pitch, and roll), quaternions, and sensor data. Quaternions uniquely define orientation and, unlike Euler angles, do not experience a singularity (i.e. gimbal lock) when pointing straight up. They easily can be converted to Euler angles, the rotation vector, and the rotation matrix (aka DCM), as discussed in Appendix I.

1.1 SENtral Features and Benefits

At the heart of the SENtral M&M module is PNI's revolutionary SENtral Motion Coprocessor. Listed below are some of the features and benefits of this device.

- **Low power consumption.** Offloads sensor processing from the less efficient host CPU, consuming <1% of the power of a Cortex M0 running a comparable sensor fusion algorithm. Provides the ability to tailor the tradeoff between power consumption and motion-tracking performance.
- **Industry-leading heading accuracy.** Unparalleled heading accuracy for consumer electronics applications.
- **Continuous hard and soft-iron auto-calibration.** Unlike other motion-tracking products, SENtral calibrates for both hard-iron and soft-iron magnetic distortion. Specifically, soft-iron distortion is quite difficult to correct, and can contribute up to 90° of error. It can be caused by materials widely used in mobile and consumer electronic devices, such as EMI shielding tape and other shielding. Additionally, since a host system's magnetic signature can change over time and temperature, SENtral's continuous auto-calibration ensures accuracy over time.
- **Magnetic anomaly compensation.** With SENtral, heading and motion tracking is unaffected by short-term magnetic anomalies, such as rebar in buildings, desks, speakers etc., that can easily throw off the accuracy. SENtral establishes if a transient magnetic anomaly is present and compensates for this.
- **Sensor flexibility.** SENtral works with most common consumer electronics motion sensors, so designers can choose the sensors most appropriate for their systems.

- **Small form-factor.** 1.6x1.6x0.5 mm chip-scale package on 0.4 mm pitch. Uses little PCB real estate, allowing for painless integration.
- **I²C interface.** Uses industry-standard I²C protocol in a low-power implementation to interface to the sensors and the host, so system integration is straightforward. Standard, Fast, Fast Plus, and High Speed are supported on the host bus.
- **Outputs.** SENtral natively outputs Euler angles (heading, pitch, and roll), quaternions, rotational velocity, linear acceleration, and magnetic field.
- **Pass-Through** allows for direct communication with devices on the I²C sensor bus.

1.2 SENtral M&M System Overview

Figure 1-1 provides a reference schematic for SENtral M&M modules. While this diagram applies for most versions so the SENtral M&M, the White and Blue M&M modules are significantly different. Specific schematics for each module are available from PNI. How to interface with the SENtral M&M is covered in more detail in Section 3.

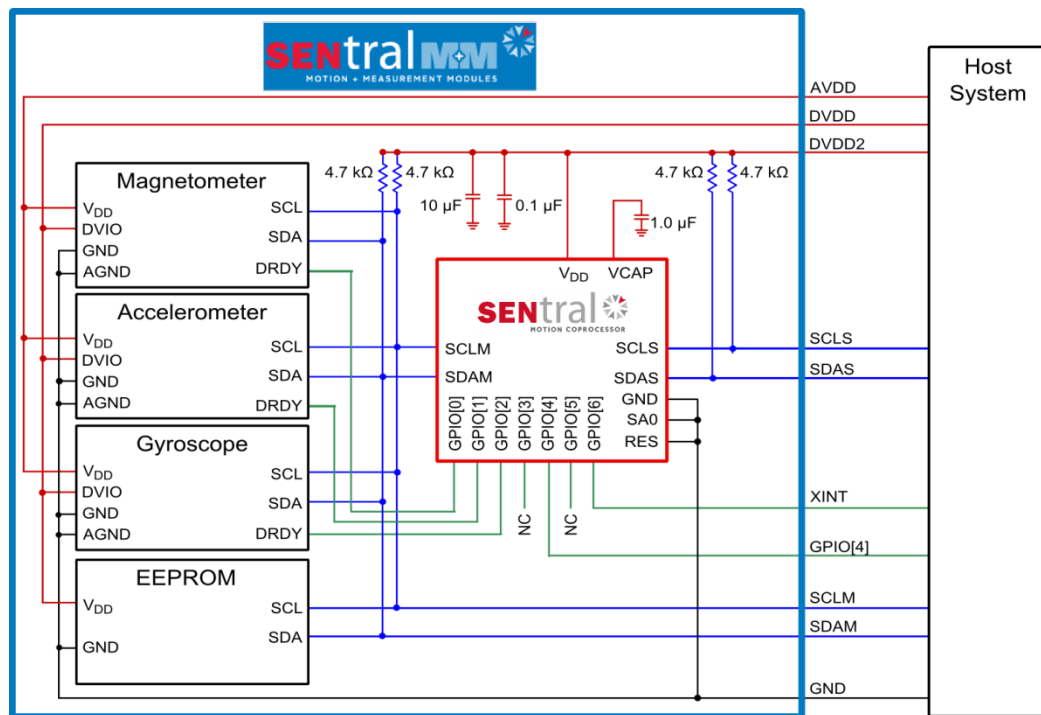


Figure 1-1: SENtral M&M Module Reference Schematic

A few points on diagram:

- The layout shows a discrete magnetometer, accelerometer, and gyroscope. SENtral M&M modules generally incorporate a combo sensor that combines the gyroscope and accelerometer into a single device or all three sensors into a single device.

- SENtral acts as a slave on a host system I²C bus. This does not need to be a dedicated bus, although it is shown this way in the schematic.
- The SCLM and SDAM lines can be used to monitor SENtral's I²C sensor bus, but this is not necessary. These lines are optional and may be left unconnected.
- If the host will poll SENtral, rather than running in an interrupt-driven manner, it is not necessary to connect GPIO[6], the host interrupt line, to the host system.
- GPIO[4] is intended for future use and currently serves no purpose. This can be left unconnected.

2 SENtral Specifications¹

2.1 Performance Characteristics

Table 2-1: Performance Characteristics

Parameter	Minimum	Typical	Maximum	Units
Heading Accuracy		2		° rms
Output Data Rate		200	400	Hz

2.2 Electrical Characteristics

Table 2-2: Absolute Maximum Ratings

Parameter	Symbol	Minimum	Maximum	Units
Supply Voltage	V_{DD}	-0.3	+3.6	VDC
Input Pin Voltage	V_{IN}	GND – 0.3	$V_{DD} + 0.3$	VDC
Storage Temperature		-50°	+150°	C

CAUTION:

Stresses beyond those listed above may cause permanent damage to the device. These are stress ratings only. Operation of the device at these or other conditions beyond those indicated in the operational sections of the specifications is not implied.

Footnote

1. Specifications subject to change.

Table 2-3: Operating Conditions

Parameter		Symbol	Min	Typ	Max	Units
Digital Supply Voltage – Sensors & EEPROM		DVDD	1.71		AVDD	VDC
Supply Voltage – SENtral		DVDD2	1.6		3.3	VDC
Analog Supply Voltage – Sensors		AVDD	2.4		3.6	VDC
Power-On Reset Threshold		V _{POR}		1.0		VDC
High Level Input Voltage		V _{IH}	0.7*V _{DD}		V _{DD}	VDC
Low Level Input Voltage		V _{IL}	0		0.3*V _{DD}	VDC
High Level Output Current, V _{OH} = V _{DD} – 0.3V		I _{OH}			-1	mA
Low Level Output Current, V _{OL} = 0.3V		I _{OL}	1			mA
I ² C Interface Data Rate ¹	Host Bus				3400	kbits/sec
	Sensor Bus				1000	kbits/sec
	Pass-Through				400	kbits/sec
Operating Temperature		T _{OP}	-40	+25	+85	C

Footnote:

1. SENtral's I²C Host Interface supports Standard, Fast, Fast Plus, and High Speed Modes. High Speed Mode (3400 kHz) is supported with a reduced range of V_{DD} and bus capacitance. SENtral's I²C sensor bus interface supports Standard, Fast, and Fast Plus Modes. Pass-Through state, which connects the sensor bus and host bus, supports Standard and Fast Modes.

3 Interface

The SENtral M&M pin-out is given in Table 3-1. The same pin-outs also are given alongside the device mechanical drawings in Section 5. See Table 2-3 for the operating ranges of DVDD, DVDD2, and AVDD. A discussion of the communication interface follows the table.

Table 3-1: SENtral M&M Module Pin Assignments

Pin Name	Description	Orange, Red, Green, Yellow Pin#	White Pin #	Blue Pin #
DVDD	Digital Supply Voltage – Sensors & EEPROM	1	NA	2
DVDD2	Supply Voltage – SENtral	2	D1	2
AVDD	Analog Supply Voltage – Sensors	7	NA	7
GND	Ground	8	D2	8
SCLS	I ² C host bus SCL clock line	3	B1	3
SDAS	I ² C host bus SDA data line	5	A1	5
SDAM	I ² C sensor bus SDA data line	9	A4	9
SCLM	I ² C sensor bus SCL clock line	10	B4	10
GPIO[0]	SENtral Accelerometer Interrupt	--	D4	--
GPIO[1]	SENtral Magnetometer Interrupt	--	C4	--
GPIO[2]	SENtral Gyroscope Interrupt	--	A3	--
GPIO[3]	Reserved	--	B3	--
GPIO[4]	Reserved	6	A2	6
GPIO[5]	Reserved	--	B2	--
GPIO[6]	Host Event Interrupt	4	C1	4
SA0	Slave Address Pin 0	--	C3	--
VCAP	Regulator Capacitor	--	D3	--
Reserved	Reserved (not connected)	--	C2	1, 12, 13

Communication with the host processor is via SENtral's I²C host interface. The SENtral M&M acts as a slave device while the host processor acts as the master. The host interrupt line lets the host system know when SENtral has updated measurement data. The SENtral motion coprocessor on the SENtral M&M module communicates with the module's sensors over the sensor bus, where SENtral acts as the I²C master and the sensors act as I²C slave devices.

Understanding how the sensor bus operates is not necessary when using the SENtral M&M module, but it may be useful if operating in Pass-Through state.

SENtral's I²C interfaces comply with NXP's UM10204 specification and user manual, rev 04. Standard, Fast, Fast Plus, and High Speed modes of the I²C protocol are supported by SENtral's I²C host interface. Below is a link to this document.

http://www.nxp.com/documents/user_manual/UM10204.pdf

3.1 I²C Timing

SENtral's I²C timing requirements are set forth below, in Figure 3-1 and Table 3-2. For the timing requirements shown in Figure 3-1, transitions are 30% and 70% of V_{DD}.

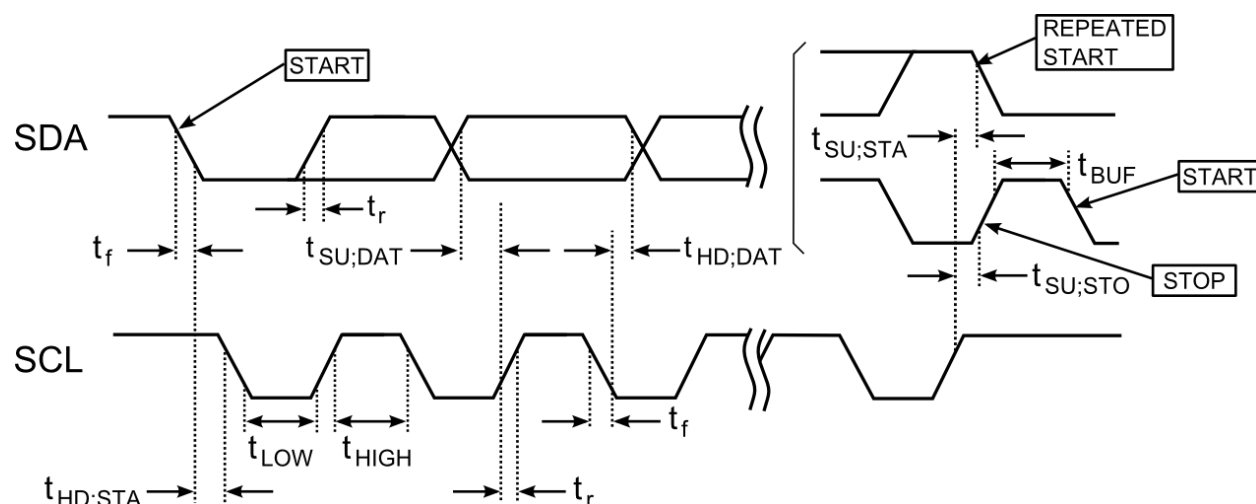


Figure 3-1: I²C Timing Diagram

Table 3-2: I²C Timing Parameters

Symbol	Parameter	Standard		Fast		Fast Plus		Units
		Min	Max	Min	Max	Min	Max	
f _{SCL}	SCL Clock	0	100	0	400	0	1000	kHz
t _r	SDA & SCL Rise Time	-	1000	20	300		120	ns
t _f	SDA & SCL Fall Time	-	300	20*(V _{DD} /5.5V)	300	20*(V _{DD} /5.5V)	120	ns
t _{LOW}	LOW period of SCL Clock	4.7	-	1.3	-	0.5	-	μs
t _{HIGH}	HIGH period of SCL Clock	4.0	-	0.6	-	0.26	-	μs
t _{HD;STA}	Hold time (repeated) START	4.0	-	0.6	-	0.26	-	μs
t _{HD;DAT}	Data hold time	0	-	0	-	0	-	μs
t _{SU;DAT}	Data set-up time	250	-	100	-	50	-	ns
t _{SU;STA}	Set-Up time for repeated Start	4.7	-	0.6	-	0.26	-	μs
t _{SU;STO}	Stop set-up time	4.0	-	0.6	-	0.26	-	μs
t _{BUF}	Bus free time between STOP & START	4.7	-	1.3	-	0.5	-	μs

3.2 I²C Host Interface (Host Bus)

The host will control the SENtral M&M on the host bus via SENtral's I²C host interface. The host interface consists of 2 wires: the serial clock, SCLS, and the serial data line, SDAS. Both lines are bi-directional. SENtral is connected to the host bus via the SDAS and SCLS pins, which incorporate open drain drivers within the device. Note the SENtral M&M module incorporates 4.7 kΩ pull-up resistors on the host bus clock and data lines, so if the host system also incorporates pull-up resistors on these line the resistors will act in parallel.

The SENtral M&M's **7-bit** I²C slave address is 0x28 (0b0101000).

Data transfer is always initiated by the host. Data is transferred between the host and SENtral serially through the data line (SDAS) in an 8-bit transfer format. The transfer is synchronized by the serial clock line, SCLS. Supported transfer formats are single-byte read, multiple-byte read, single-byte write, and multiple-byte write. The data line can be driven

either by the host or SENtral. Normally the serial clock line will be driven by the host, although exceptions can exist when clock-stretching is implemented in Pass-Through State.

3.2.1 I²C Transfer formats

Figure 3-2 illustrates writing data to registers in single-byte or multiple-byte mode.

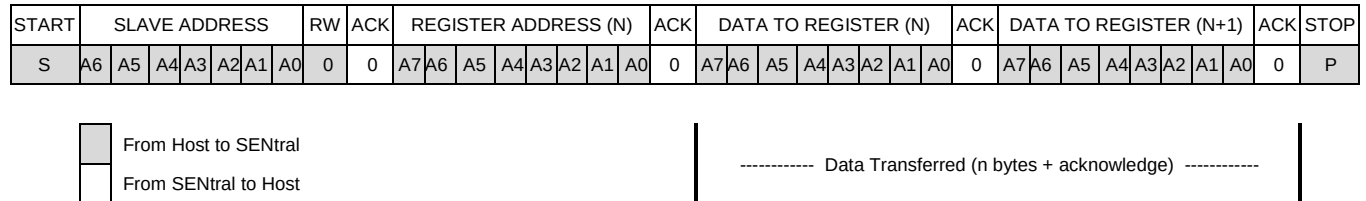


Figure 3-2: I²C Slave Write Example

The I²C host interface supports both a read sequence using repeated START conditions, shown in Figure 3-3, and a sequence in which the register address is sent in a separate sequence than the data, shown in Figure 3-4.

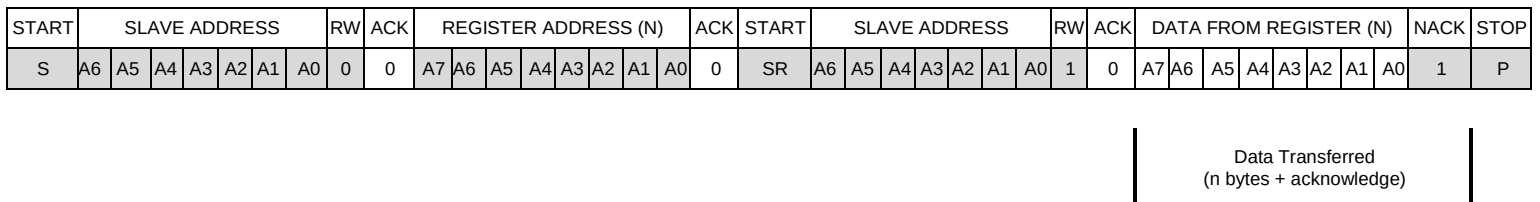


Figure 3-3: I²C Slave Read Example, with Repeated START

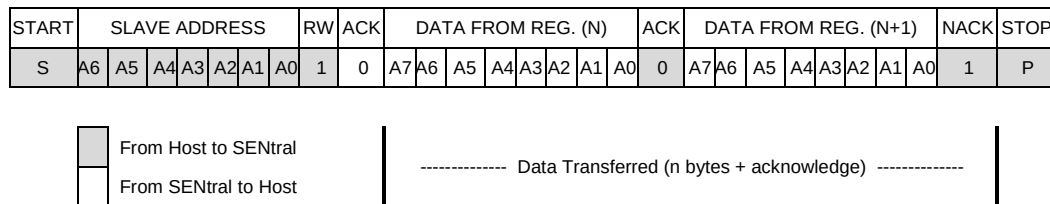


Figure 3-4: I²C Slave read register from current address

3.3 I²C Sensor Interface (Sensor Bus)

The SENtral motion coprocessor on the SENtral M&M module communicates with the module's accelerometer, gyroscope, and magnetometer over the module's sensor bus, where SENtral acts as the I²C master and the sensors act as I²C slave devices. Understanding how the sensor bus operates is not necessary when using the SENtral M&M module, but it may be useful if operating in Pass-Through state to communicate directly with a sensor or the EEPROM.

On the sensor bus, SENtral initiates data transfer and generates the serial clock. SENtral's I²C sensor interface supports Standard mode with a rate up to 100 kbit/s, Fast mode with a rate up to 400 kbit/s, and Fast Plus mode with a rate up to 1000 kbit/s.

The two wires comprising the sensor bus are SDAM, the serial data line, and SCLM, the serial clock. Both are bidirectional and driven by open drain transistors within SENtral. These can be monitored by the host, but should not be written to by the host. Each line is attached to a 4.7 kΩ pull-up resistor.

3.4 Host Interrupt/GPIO Lines

GPIO[6] provides an interrupt to the host whenever a defined event occurs. Exactly which types of events will trigger an interrupt are set by the EnableEvents register, which is discussed in Section 4.2. This interrupt line can be used to signal the host that new results are available for reading. Alternately, the host may poll SENtral's EventStatus register, discussed in Section 4.3, to determine if any events of interest have been updated. If polling will be used, PNI recommends polling on a regular interval such that an error event will be quickly identified.

GPIO[4] is not currently used, and generally should be left unconnected. This is also true for GPIO[3] and GPIO[5], which are only accessible on the SENtral White M&M.

4 Operation

Figure 4-1 provides a flow chart of the SENtral M&M module's initialization process, and a discussion of this process follows in Section 4.1

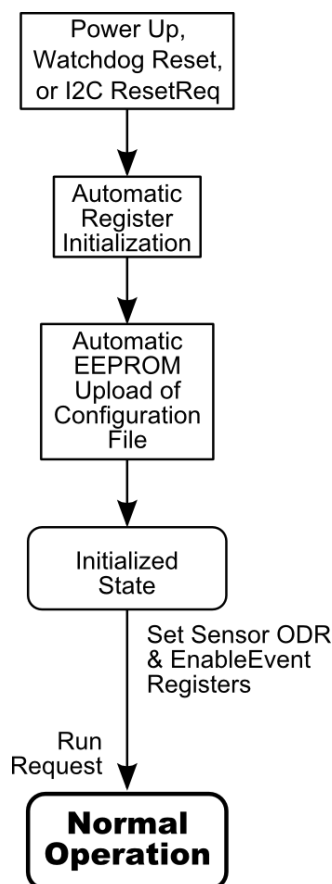


Figure 4-1: SENtral Initialization Sequence

Once the initialization sequence is complete, there are three states in which SENtral may reside: Normal Operation, Standby, and Pass-Through. Figure 4-2 indicates the recommended way to get from one state to another, and these states are discussed in detail in Sections 4.2 and 4.3 (Normal Operation), 4.4 (Standby), and 4.5 (Pass-Through).

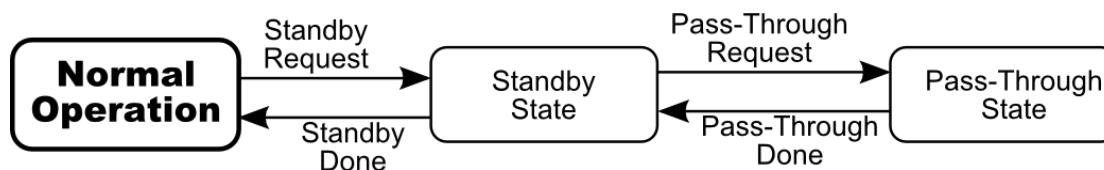


Figure 4-2: SENtral Operational States

4.1 Power-Up

After powering up or issuing a ResetReq command, SENtral automatically initializes the registers and loads the SENtral Configuration File from the onboard EEPROM., as indicated in Figure 4-1. The Configuration File contains information specific to the particular SENtral M&M flavor, and is discussed more thoroughly in the SENtral Motion Coprocessor Technical Datasheet. Once the upload is complete, SENtral enters Initialized State and waits for instructions from the host.

Table 4-1: Configuration File Upload from EEPROM Registers

Register Name	Address	Register Value
SentralStatus	0x37	[0] EEPROM. 1 = EEPROM detected [1] EEUploadDone. 1 = EEPROM upload completed [2] EEUploadError. 1 = Calculated CRC of EEPROM is correct. Only valid when EEUploadDone = 1. [3] Idle. 1 = Device in Unprogrammed or Initialized state. [4] NoEEPROM. 1 = No EEPROM detected.
ResetReq	0x9B	[0] ResetRequest. 1 = Emulate a hard power down/power up.

The host should confirm a successful EEPROM upload by following the steps below:

- Read the value from the SentralStatus register.
- Check bit [0], the EEPROM bit, to ensure an EEPROM is detected by SENtral.
- Check bit [1], the EEUploadDone bit. If this is '0' then the Configuration File upload is not complete, and reread the SentralStatus register until bit [1] = 1.
- Once bit [1] = 1, check bit [2], the EEUpload Error bit. If this is '0', then the upload was successful.

If the Configuration File upload failed, send a Reset command by writing 0x01 to the ResetReq register. If the issue persists, refer to the SENtral Motion Coprocessor datasheet for debugging hints.

4.2 Initial Register Set-Up

After the initialization process is complete, it is necessary to configure a few of SENtral's registers before running in Normal Operation. These registers are given in Table 4-2.

Table 4-2: Registers for Initial Set-up

Register Name	Address	Register Value
MagRate	0x55	Requested magnetometer output data rate
AccelRate	0x56	Requested accelerometer output data rate divided by 10
GyroRate	0x57	Requested gyroscope output data rate divided by 10
QRateDivisor	0x32	Along with GyroRate, establishes output data rate for quaternion data.
AlgorithmControl	0x54	[0] 1 = StandbyEnable 0 = Disable Standby State [1] RawDataEnable. 1 = Raw data provided in MX, MY, MZ, AX, AY, AZ, GX, GY, & GZ. 0 = Scaled sensor data. [2] HPRoutput. 1 = Heading, pitch, and roll output in QX, QY, & QZ. QW = 0.0. 0 = Quaternion outputs.
EnableEvents	0x33	'1' indicates an interrupt to the host will be generated for the event. [0] CPUReset. Non-maskable [1] Error [2] QuaternionResult [3] MagResult [4] AccelResult [5] GyroResult

Perform the following operations to run SENtral as desired.

- Set the sensor output data rates (ODRs): MagRate, AccelRate, and GyroRate. If a sensor rate is set to 0x00, SENtral will shutdown the sensor and disable SENtral background calibration. There are two major points regarding setting these registers:
 - The AccelRate and GyroRate register values should be $1/10^{\text{th}}$ the desired rate, while the MagRate value should match the desired ODR. For example, if the desired ODR is 30 Hz for the magnetometer, 100 Hz for the accelerometer, and 200 Hz for the gyroscope, then the respective register values should be 0x1E (30_d), 0x0A (10_d), and 0x14 (20_d).
 - The actual accelerometer and gyro ODRs are limited to the ODRs supported by the specific sensors. **If the AccelRate or GyroRate register values do not correspond to a supported ODR, then the next highest ODR will be used.** For instance, if the GyroRate register is set to 0x14, which corresponds to 200 Hz, but the gyro supports 95 Hz, 190 Hz, and 380 Hz, then the actual gyro ODR will be 380 Hz since this is the closest supported rate above that requested by the register.

- Establish the quaternion output data rate, where the quaternion output data rate equals GyroRate divided by QRateDivisor. The default for QRateDivisor is 0x00, which is interpreted as '1' and results in the quaternion output data rate equaling GyroRate.
- Establish how SENtral's orientation and sensor data is to be output. The AlgorithmControl register allows the user to select either quaternion or Euler angles (heading, pitch, and roll) for orientation outputs, and either scaled or raw sensor data outputs. The defaults are quaternions and scaled sensor data.
- Establish which events will trigger an interrupt to the host by configuring the EnableEvent register. PNI specifically recommends enabling bit [1], the Error interrupt bit, in addition to whichever other interrupts the user wants.

Example steps to do this are below:

- Write 0x640A0F to the MagRate register. Since SENtral automatically increments to the next register, this also populates the AccelRate and GyroRate registers. This sets MagRate to 100 Hz, AccelRate to 100 Hz, and GyroRate to 150 Hz.
- Write 0x01 to the QRateDivisor Register. This sets the quaternion output data rate to equal the GyroRate. This step is optional, since the default register value of 0x00 also sets the quaternion output data rate equal to GyroRate.
- Write 0x06 to the AlgorithmControl register. This enables heading, pitch, and roll orientation outputs and raw sensor data outputs. This step is optional, as the default register value of 0x00 results in outputs of quaternions and scaled sensor data.
- Write 0x07 to the EnableEvents register. This sets the host to receive interrupts from SENtral whenever the quaternion results registers (QX, QY, QZ, and QW) are updated, an error has been detected, or SENtral has been Reset but the Configuration File has not been uploaded. If the host will regularly poll SENtral, rather than run in an interrupt-driven manner, it is not necessary to set the EnableEvents register.

4.3 Running in Normal Operation

After performing the steps listed above, SENtral is ready to start generating orientation data. The registers used to run in Normal Operation are given in Table 4-2, the steps to follow comes after this, and a flow diagram is given in Figure 4-3.

Table 4-3: Normal Operation Registers

Register Name	Address	Register Value
HostControl	0x34	[0] 1 = RunEnable 0 = Enable Initialized State
EventStatus	0x35	'1' indicates a new event has been generated. [0] CPUReset [1] Error [2] QuaternionResult [3] MagResult [4] AccelResult [5] GyroResult

Below are the steps to follow when operating in Normal Operation state.

- Write 0x01 to the HostControl register. This sets the RunEnable bit to '1' and enables the sensors and the SENtral algorithm.
- If operating in an interrupt-driven mode, then the host waits until it receives an interrupt signal from SENtral. Alternatively the host may operate on a polling basis, rather than an interrupt-driven basis, in which case the interrupt line may not be used.
- Once an interrupt is received by the host or the host otherwise decides to read new data, read the EventStatus register.
- Interpret and act on the EventStatus register in the priority shown in Figure 4-3. If bit [1], the Error bit, is '1', see Section 4.3.1. If bits [2], [3], [4], or [5], the Results bits, are '1', see Section 4.3.2. Bit [0], the CPUReset bit, should never be '1', since this bit only can be '1' after a Reset or powering up and prior to loading the Configuration File, and on the SENtral M&M module loading of the Configuration File is automatically performed after powering up.
- Repeat steps c and d until new orientation data is not needed and/or the host decides to enter a different state.

Reading the EventStatus register clears it. It is possible for more than one bit position to be '1' in the EventStatus register, especially if the host does not always read the EventStatus register after receiving an interrupt. Similarly, if multiple bits are set to '1' in the EventStatus register, once the register is read all the bits will be set to '0'. For this reason the EventStatus register should be processed in the priority shown in Figure 4-3, as information will be cleared for events that are not handled.

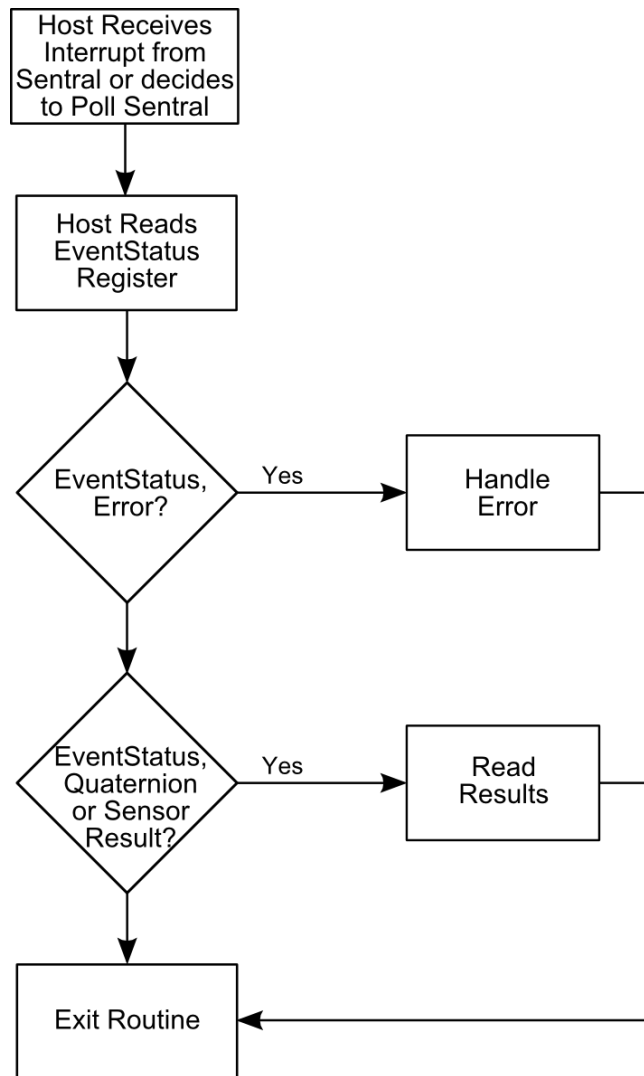


Figure 4-3: SENtral Normal Operation Flow

A discussion of how to handle the events follows.

4.3.1 Error

In the event of an error, SENtral will trigger an error interrupt and SENtral will enter Standby State. See the Section 4.6 for recommendations on Troubleshooting and/or reset SENtral by sending 0x01 to the ResetReq register, at address 0x9B.

4.3.2 Read Results

The Results Registers' addresses, formats, and full-scale ranges are given below in Table 4-4. For an explanation of how to convert quaternions to the rotation vector, the rotation

matrix, or Euler angles (heading, pitch, and roll), see Appendix I. The resolution is 32 kHz for all timestamps.

Note: All multi-byte elements are stored and transmitted using the Little Endian convention: the least significant byte is stored at the lowest address and transmitted first over the I²C bus.

Table 4-4: Results Registers

Name	Address (Hex)	Description	Format	Full-Scale Range
QX	00 – 03	Normalized Quaternion – X, or Heading	Float32	0.0 – 1.0, or $\pm\pi$
QY	04 – 07	Normalized Quaternion – Y, or Pitch	Float32	0.0 – 1.0, or $\pm\pi/2$
QZ	08 – 0B	Normalized Quaternion – Z, or Roll	Float32	0.0 – 1.0, or $\pm\pi$
QW	0C – 0F	Normalized Quaternion – W, or 0.0	Float32	0.0 – 1.0
QTime	10 – 11	Quaternion Data Timestamp	UInt16	0 – 2048 msec
MX	12 – 13	Magnetic Field – X Axis, or Raw Mag Data	Int16	$\pm 1000\ \mu\text{T}$ when scaled
MY	14 – 15	Magnetic Field – Y Axis, or Raw Mag Data	Int16	$\pm 1000\ \mu\text{T}$ when scaled
MZ	16 – 17	Magnetic Field – Z Axis, or Raw Mag Data	Int16	$\pm 1000\ \mu\text{T}$ when scaled
MTime	18 – 19	Magnetometer Interrupt Timestamp	UInt16	0 – 2048 msec
AX	1A – 1B	Linear Acceleration – X Axis, or Raw Accel Data	Int16	$\pm 16\ \text{g}$ when scaled
AY	1C – 1D	Linear Acceleration – Y Axis, or Raw Accel Data	Int16	$\pm 16\ \text{g}$ when scaled
AZ	1E – 1F	Linear Acceleration – Z Axis, or Raw Accel Data	Int16	$\pm 16\ \text{g}$ when scaled
ATime	20 – 21	Accelerometer Interrupt Timestamp	UInt16	0 – 2048 msec
GX	22 – 23	Rotational Velocity – X Axis, or Raw Gyro Data	Int16	$\pm 5000^\circ/\text{s}$ when scaled
GY	24 – 25	Rotational Velocity – Y Axis, or Raw Gyro Data	Int16	$\pm 5000^\circ/\text{s}$ when scaled
GZ	26 – 27	Rotational Velocity – Z Axis, or Raw Gyro Data	Int16	$\pm 5000^\circ/\text{s}$ when scaled
GTime	28 – 29	Gyroscope Interrupt Timestamp	UInt16	0.0 – 2.048 sec

4.4 Standby State

In Standby State overall system power consumption is dramatically reduced because both the SENtral algorithm and the sensors are shut down. Table 4-5 provides the registers associated with Standby State.

Table 4-5: Standby Registers

Register Name	Address	Register Value
AlgorithmControl	0x54	[0] 1 = StandbyEnable 0 = Disable Standby State
AlgorithmStatus	0x38	[0] 1 = SENtral in Standby State 0 = SENtral not in Standby State

The steps to enter and exit Standby State are given below:

- Write 0x01 to the AlgorithmControl register. This places SENtral in Standby State.
- Read the AlgorithmStatus register. If bit [0] is '1', then SENtral is in Standby State. This step is optional.
- When you are ready to exit Standby State, write 0x00 to the AlgorithmControl register. This takes SENtral out of Standby State and normally will place it back into Normal Operation.
- Read the AlgorithmStatus register. If bit [0] is '0', then SENtral is not in Standby State. This step is optional.

4.5 Pass-Through State

In Pass-Through State, SENtral's sensor and host interfaces are connected by internal switches so the host system can communicate directly with the sensors or EEPROM. To enter Pass-Through State, SENtral first either should be in Standby or Initialized State. Consequently, in Pass-Through State the SENtral algorithm, host interrupt line, and sensors are disabled, unless a sensor is directly turned on by the host. When exiting Pass-Through State, SENtral will return to its prior state.

Note: When entering Pass-Through State the sensor's registers retain the values established by SENtral, and when exiting Pass-Through State any register changes will be retained.

Uses for the Pass-Through State include:

- Direct control of sensors, if desired.
- Debugging.
- Communication with the dedicated EEPROM, if implemented. Specifically, if a new Configuration File is generated, the host can write this into the EEPROM when in Pass-Through State, as discussed in the SENtral Motion Coprocessor datasheet.

Since operating in Pass-Through State requires stopping the SENtral algorithm, Pass-Through State is not recommended for accessing sensor data unless reliable heading data is not required. If sensor data and reliable heading data are both desired, they can both be accessed during Normal Operation from the Results Registers, as given in Table 4-4.

Table 4-6 provides the registers associated with Pass-Through State.

Table 4-6: Pass-Through Registers

Register Name	Address	Register Value
AlgorithmControl	0x54	[0] 1 = StandbyEnable 0 = Disable Standby State
AlgorithmStatus	0x38	[0] 1 = SENtral in Standby State 0 = SENtral not in Standby State
PassThroughControl	0xA0	[0] 1 = Enable Pass-Through State 0 = Disable Pass-Through State
PassThroughStatus	0x9E	[0] 1 = SENtral in Pass-Through State. 0 = SENtral not in Pass-Through State.

The steps to go in and out of Pass-Through State are given below.

- Write 0x01 to the AlgorithmControl register. This places SENtral in Standby State.
- Write 0x01 to the PassThroughControl register. This places SENtral in Pass-Through State.
- Read the PassThroughStatus register. If bit [0] is '1', then SENtral is in Pass-Through State. This step is optional.
- When you are done in Pass-Through State, write 0x00 to the PassThroughControl register. This terminates Pass-Through mode and returns SENtral to Standby State.
- Write 0x00 to the AlgorithmControl register. This takes SENtral out of Standby State and normally will place it back into Normal Operation.

4.6 Troubleshooting

This section provides guidance in troubleshooting SENtral, and is divided into hardware-related and software-related errors.

4.6.1 Hardware-Related Error Conditions

Possible indications of a hardware-related problem are given below in Table 4-7.

Table 4-7: Hardware-Related Error Indications

Register Name	Address	Error Indication
EventStatus	0x35	[0] 1 = CPURest. SENtral Configuration File needs uploading. See Section 4.1.
SentralStatus	0x37	[2] 1 = EEUploadError. Issue with uploading from the dedicated EEPROM. See Section 4.1.
MagRate	0x55	0x00 – Value lost
AccelRate	0x56	0x00 – Value lost
GyroRate	0x57	0x00 – Value lost

In the event of such errors, SENtral will enter Standby State, shut down the sensors, and generate an interrupt to the host. Possible reasons for hardware-related errors include problems with the EEPROM upload, power transients detected by power management, and errors in software detected by Watchdog. Often the error can be cleared by sending the ResetReq command.

4.6.2 Software-Related Error Conditions

Possible indications of software-related errors are given below in Table 4-8:

Table 4-8: Software-Related Error Indications

Register Name	Address	Error Indication
EventStatus	0x35	[1] 1 = Error.
SensorStatus	0x36	[0] MagNACK. 1 = NACK from magnetometer [1] AccelNACK. 1 = NACK from accelerometer [2] GyroNACK. 1 = NACK from gyroscope [4] MagDeviceIDErr. 1 = Unexpected DeviceID from magnetometer [5] AccelDeviceIDErr. 1 = Unexpected DeviceID from accelerometer [6] GyroDeviceIDErr. 1 = Unexpected DeviceID from gyroscope.
SentralStatus	0x37	[3] 1 = Idle. SENtral in Initialized State.
ErrorRegister	0x50	Non-zero value indicated an error. See Table 4-9.

If the ErrorRegister indicates a non-zero value, then the value provides additional information on the sensor that is causing a problem, as given in Table 4-9.

Table 4-9: ErrorRegister Indications

Value	Error Condition	Response
0x00	No error	
0x80	Invalid sample rate selected	Check sensor rate settings.
0x30	Mathematical Error	Check for software updates
0x21	Magnetometer initialization failed	This error can be caused by a wrong driver, physically bad sensor connection, or incorrect I ² C device address in the driver
0x22	Accelerometer initialization failed	
0x24	Gyroscope initialization failed	
0x11	Magnetometer rate failure	This error indicates the given sensor is unreliable and has stopped producing data.
0x12	Accelerometer rate failure	
0x14	Gyroscope rate failure	

5 Package Information

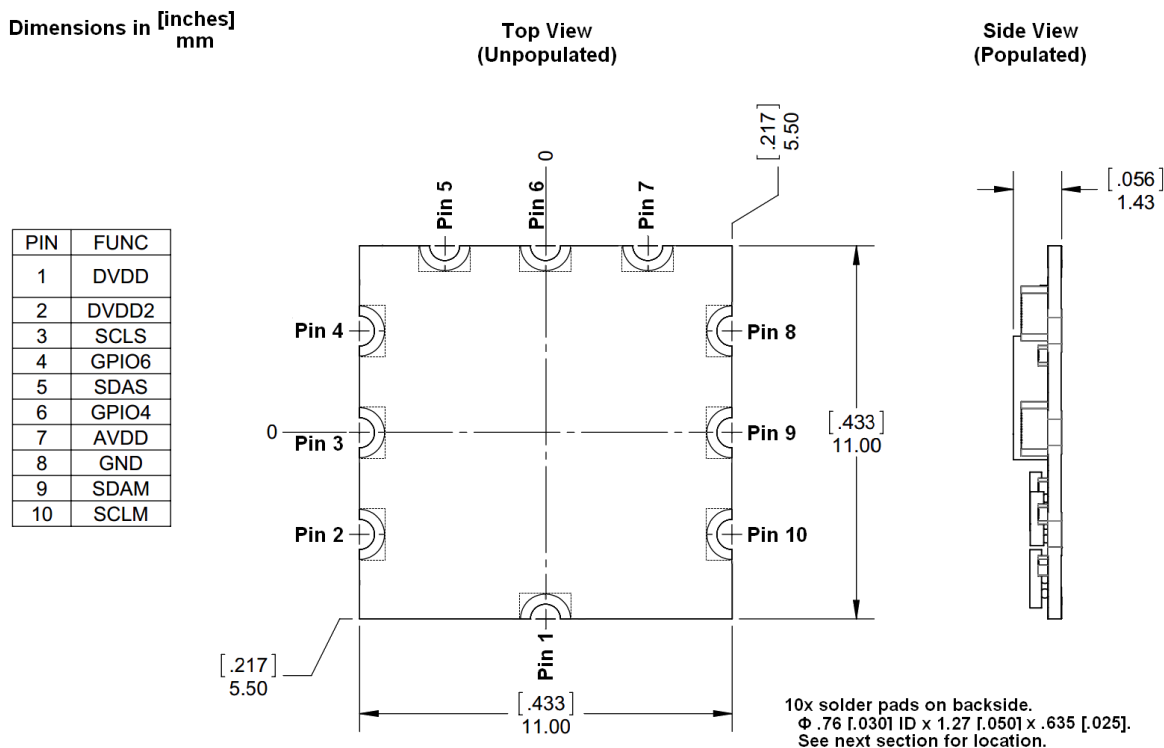


Figure 5-1: SENtral Orange, Red, Green, & Yellow M&M Mechanical Drawing

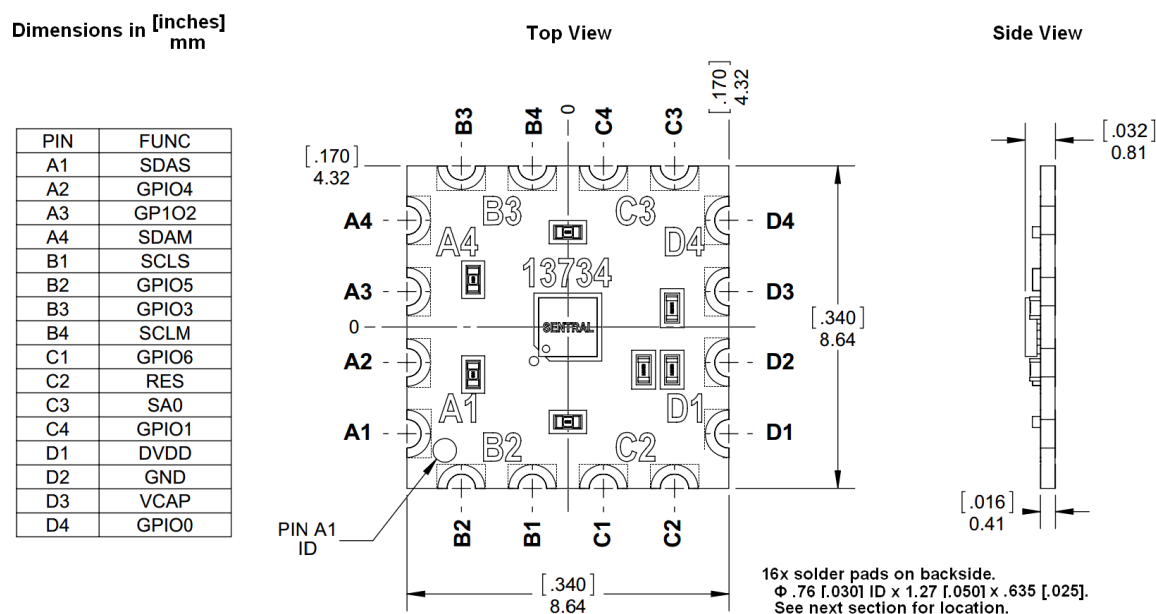
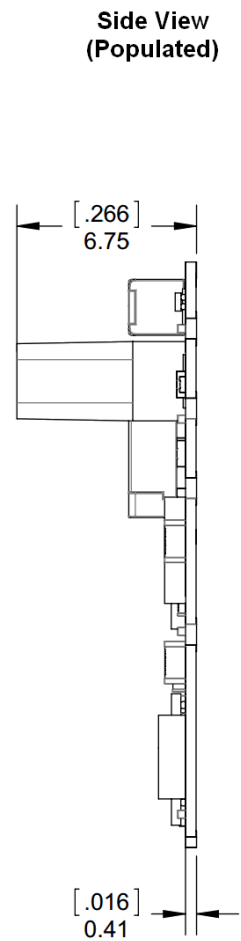
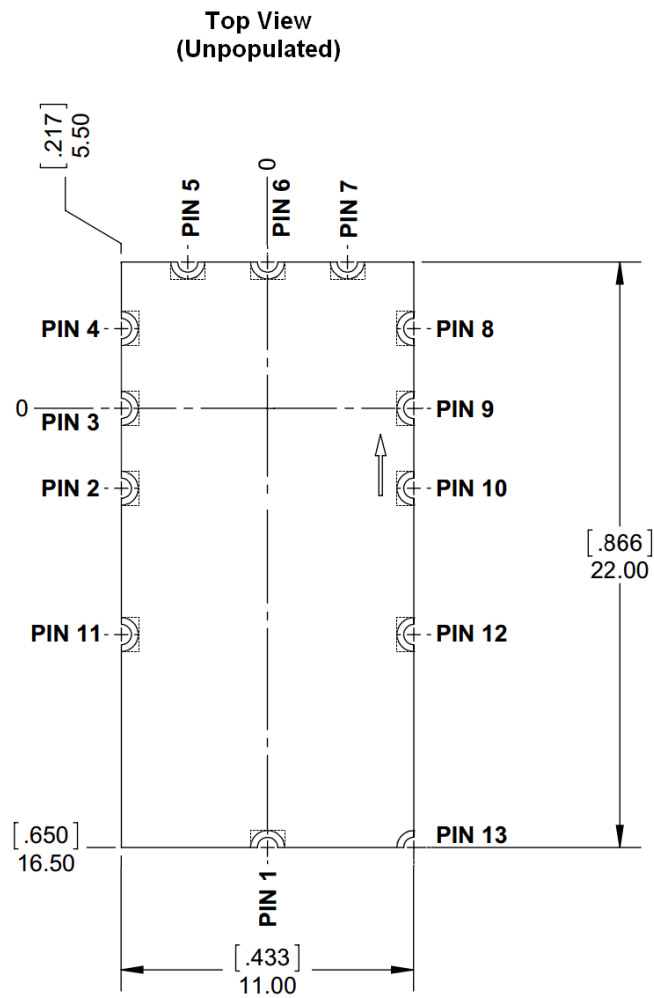


Figure 5-2: SENtral White M&M Mechanical Drawing

Dimensions in [inches]
mm

PIN	FUNC
1	N/C
2	DVDD
3	SCLS
4	GPIO6
5	SDAS
6	GPIO4
7	AVDD
8	GND
9	SDAM
10	SCLM
11	GND
12	N/C
13	N/C



13x solder pads on backside.
 $\Phi .76$ [.030] ID x 1.27 [.050] x .635 [.025].
 See next section for location.

Figure 5-3: SENtral Blue M&M Mechanical Drawing

6 Assembly Guidelines

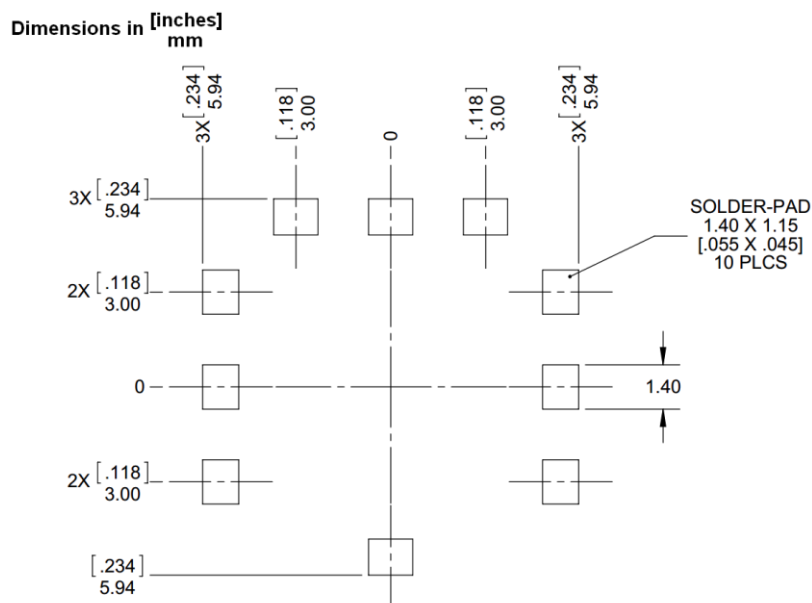


Figure 6-1: SENtral Orange, Red, Green, & Yellow M&M Solder Pad Layout

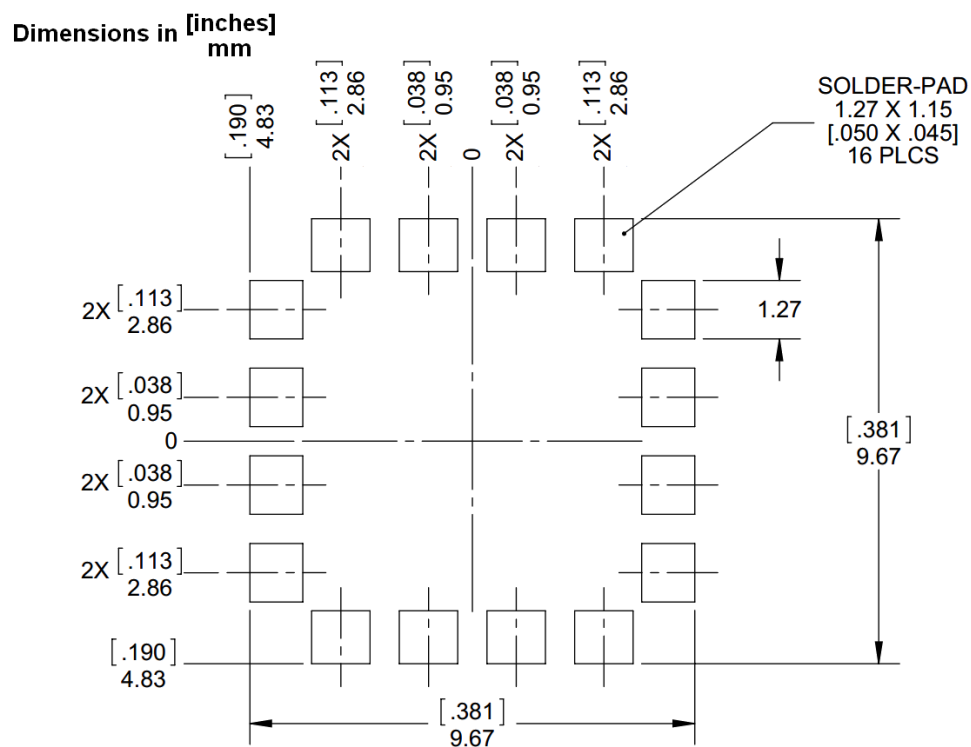


Figure 6-2: SENtral White M&M Solder Pad Layout

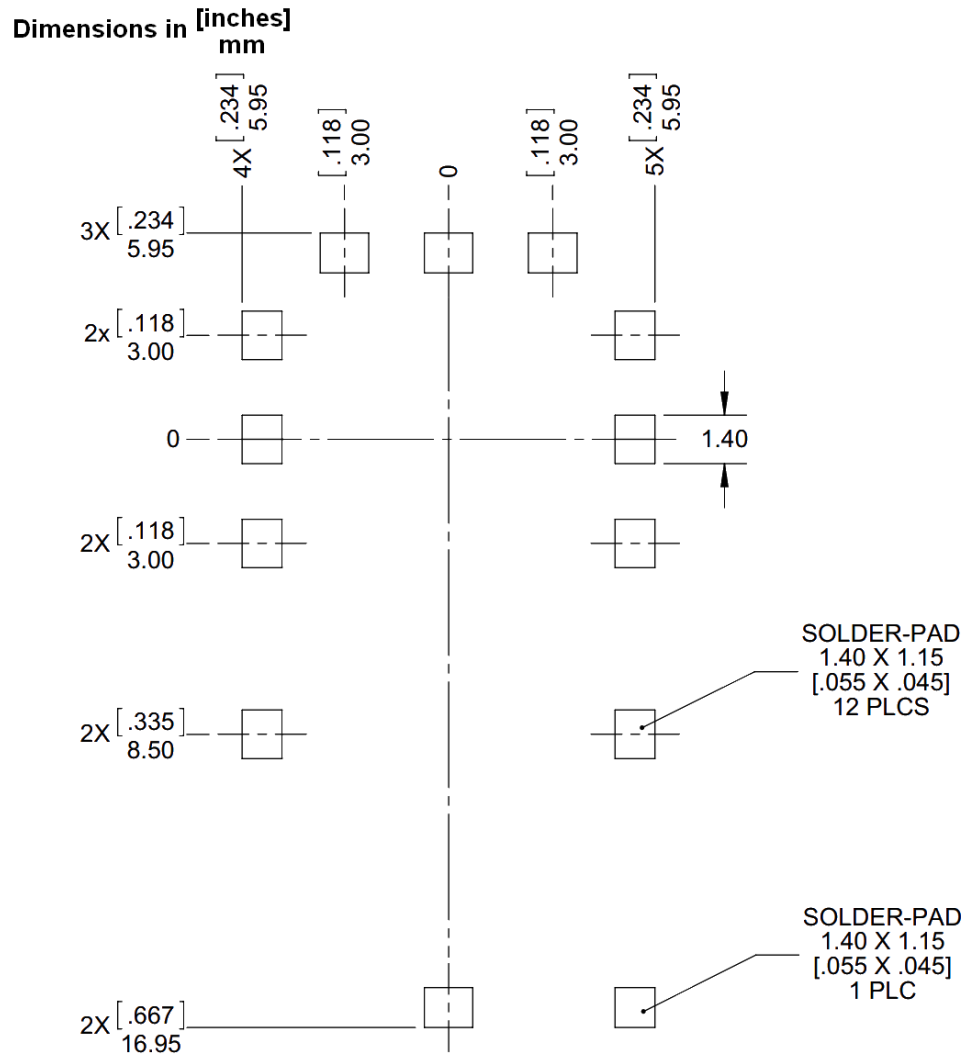


Figure 6-3: SENtral Blue M&M Solder Pad Layout

Appendix I – Converting Quaternions

SENtral outputs orientation data in quaternions, using a North-East-Down (NED) convention. This is done to avoid the singularities inherent in using Euler angles (heading, pitch, and roll), and because the fusion algorithms are easier to implement with quaternions. However, normally quaternions are not the desired final output format. Most end users will want heading, pitch, and roll, while Android looks for a rotation vector and generally uses a rotation matrix for orientation. Plus, Android and Win8 both expect data to be presented in the East-North-Up (ENU) convention. This appendix discusses how to convert SENtral's output quaternions into these other output formats.

Converting from NED to ENU

While the North-East-Down (NED) convention is common in many industries, both Android and Windows 8 use the East-North-Up convention. Below is the equation to convert from NED to ENU.

$$Q_{\text{ENU}} = \begin{pmatrix} 0.707 & 0.707 & 0 & 0 \end{pmatrix} \begin{pmatrix} Q_w & -Q_z & Q_y & -Q_x \\ Q_z & Q_w & -Q_x & -Q_y \\ -Q_y & Q_x & Q_w & -Q_z \\ Q_x & Q_y & Q_z & Q_w \end{pmatrix}_{\text{NED}} \begin{pmatrix} 0 & 0 & -0.707 & 0.707 \\ 0 & 0 & 0.707 & 0.707 \\ 0.707 & -0.707 & 0 & 0 \\ -0.707 & -0.707 & 0 & 0 \end{pmatrix}$$

Heading, Pitch, and Roll

Most end users will want orientation data reported as heading, pitch, and roll. Below are the Excel transformation equations. Note that for other programs, such as Matlab, the ATAN2 arguments may be reversed.

- Heading = atan2[($Q_x^2 - Q_y^2 - Q_z^2 + Q_w^2$), $2*(Q_xQ_y + Q_zQ_w)$]
- Pitch = asin[$-2*(Q_xQ_z - Q_yQ_w)$]
- Roll = atan2[($-Q_x^2 - Q_y^2 + Q_z^2 + Q_w^2$), $2*(Q_xQ_w + Q_yQ_z)$]

Where:

- Results are in radians.
- The quaternions are the outputs from SENtral in NED convention.
- Heading increases as the device rotates clockwise around a positive Z axis, and the range is $0^\circ - 360^\circ$. (i.e. it matches what you would expect on a compass.)
- Pitch increases when pitching upward and the range is $\pm 180^\circ$.
- Roll increases when rolling clockwise and the range is $\pm 90^\circ$.

Rotation Vector

The rotation vector is the first three elements of the quaternion output, Q_x , Q_y , and Q_z . The fourth element, Q_w , is not included in the rotation vector. The rotation vector in ENU convention will be the first three elements of Q_{ENU} , discussed above.

Rotation Matrix, or Direction Cosine Matrix (DCM)

The rotation matrix, also known as the direction cosine matrix (DCM), can be established from the quaternion output using the following conversion. Q_{ENU} values can be substituted to give the rotation matrix with an ENU convention.

$$R = \begin{array}{|c|c|c|} \hline Q_w^2 + Q_x^2 - Q_y^2 - Q_z^2 & 2*(Q_x*Q_y + Q_w*Q_z) & 2*(Q_x*Q_z - Q_w*Q_y) \\ \hline 2*(Q_x*Q_y - Q_w*Q_z) & Q_w^2 - Q_x^2 + Q_y^2 - Q_z^2 & 2*(Q_y*Q_z + Q_w*Q_y) \\ \hline 2*(Q_x*Q_z + Q_w*Q_y) & 2*(Q_y*Q_z - Q_w*Q_y) & Q_w^2 - Q_x^2 - Q_y^2 + Q_z^2 \\ \hline \end{array}$$

Appendix II – Measuring Current Consumption

All SENtral M&M modules, except the White and Blue versions, have two distinct electrical supply lines. One line is for both the EEPROM and the sensors, and one is for just SENtral. The pins for these voltages are labeled DVDD and DVDD2, respectively. To measure the current on these lines, PNI recommends placing a $1\ \Omega$ resistor in series with the DVDD pin to measure combined current consumption for the EEPROM and sensors, and a $100\ \Omega$ resistor in series with the DVDD2 pin to measure current consumption by SENtral.

The SENtral Blue M&M has a single DVDD pin that supplies current for SENtral, the EEPROM and the sensors. However, the current consumption of only the SENtral motion coprocessor can be measured by modifying the module, as given in the two options listed below.

1. Replace a zero-ohm resistor with a $100\ \Omega$ resistor and measure voltage across the resistor.
2. Remove the zero-ohm resistor, then solder wires in series with a connected ammeter.

The location of the zero-ohm resistor is given below, and a discussion of the two implementation methods follows.



Figure A-1: SENtral Blue M&M Zero-Ohm Resistor Location

Method 1: Replace zero-ohm resistor with $100\ \Omega$ resistor.

This method provides flexibility in terms of measuring with either a voltmeter or an oscilloscope, although it may be slightly difficult to implement as holding the probes in the proper position can be tricky. As long as the resistor is $\leq 100\ \Omega$, there is no need to remove it, as it should not affect performance.

To measure average current consumption, simply touch either side of the 100 Ω resistor with the voltmeter's probe tips and measure the voltage drop. Convert to current consumption using: $\mu\text{A} = 10 \cdot \text{mV}$, assuming a 100 Ω resistor.

It is possible to observe the current consumption waveform using an oscilloscope. In this case, place a 100 μF capacitor in parallel with the 100 Ω resistor. This reduces the measurement bandwidth so the waveform can be better observed.

Note that SENtral's bypass capacitors are electrically connected nearest the device after the sense resistor or the voltage meter's resistor. This will bandlimit the measurement to ~ 1.5 kHz for a 100 Ω resistor. The onboard bypass capacitance totals 1.1 μF .

Method 2: Remove zero-ohm resistor and place ammeter in series.

This method is relatively straight forward to implement, as the probes are physically soldered to the PCB. To help prevent damage to the PCB surface pads, PNI strongly recommends implementing a strain relief for the wires.

Note that the burden voltage of a typical digital multimeter (ammeter) is $\sim 100 \mu\text{V}/\mu\text{A}$, or 100 Ω . PNI has tested such an ammeter in the Method 2 scenario and seen that it does not affect operation. Also note that negative voltages produced by transient currents are smoothed by the local bypass capacitors.

Also, it may be difficult to measure DC current using ammeters with very fast measurement times due to the periodic wake/sleep cycles of SENtral. Consequently, handheld DMMs with relatively long measurement integration times work well for making average current measurement. Precision benchtop meters with an averaging or smoothing filter also can work well.

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